

Lecture 2: Intro to Particle Detectors and Interaction of Particles with Matter

- Particle Detector Overview
 - Goals and strategies
- Interaction of Charged Particles with Matter
 - Ionization energy loss and Beta-Block
 - Landau distributions
 - Coulomb scattering
- Detecting Charged Particles
 - Proportional Counters
 - Drift Chambers
 - Silicon Detectors
 - Scintillation Counters

Next Time: Calorimeters and Accelerators

References

- K. Kleinknecht, *Particle Detectors* reprinted in Ferbel, *Experimental Techniques in High-Energy Nuclear and Particle Physics*
- Particle Data Group Reviews:
<http://www-pdg.lbl.gov/2011/reviews/rpp2011-rev-particle-detectors-accel.pdf>
<http://www-pdg.lbl.gov/2011/reviews/rpp2011-rev-passage-particles-matter.pdf>
- Web pages of all major experiments

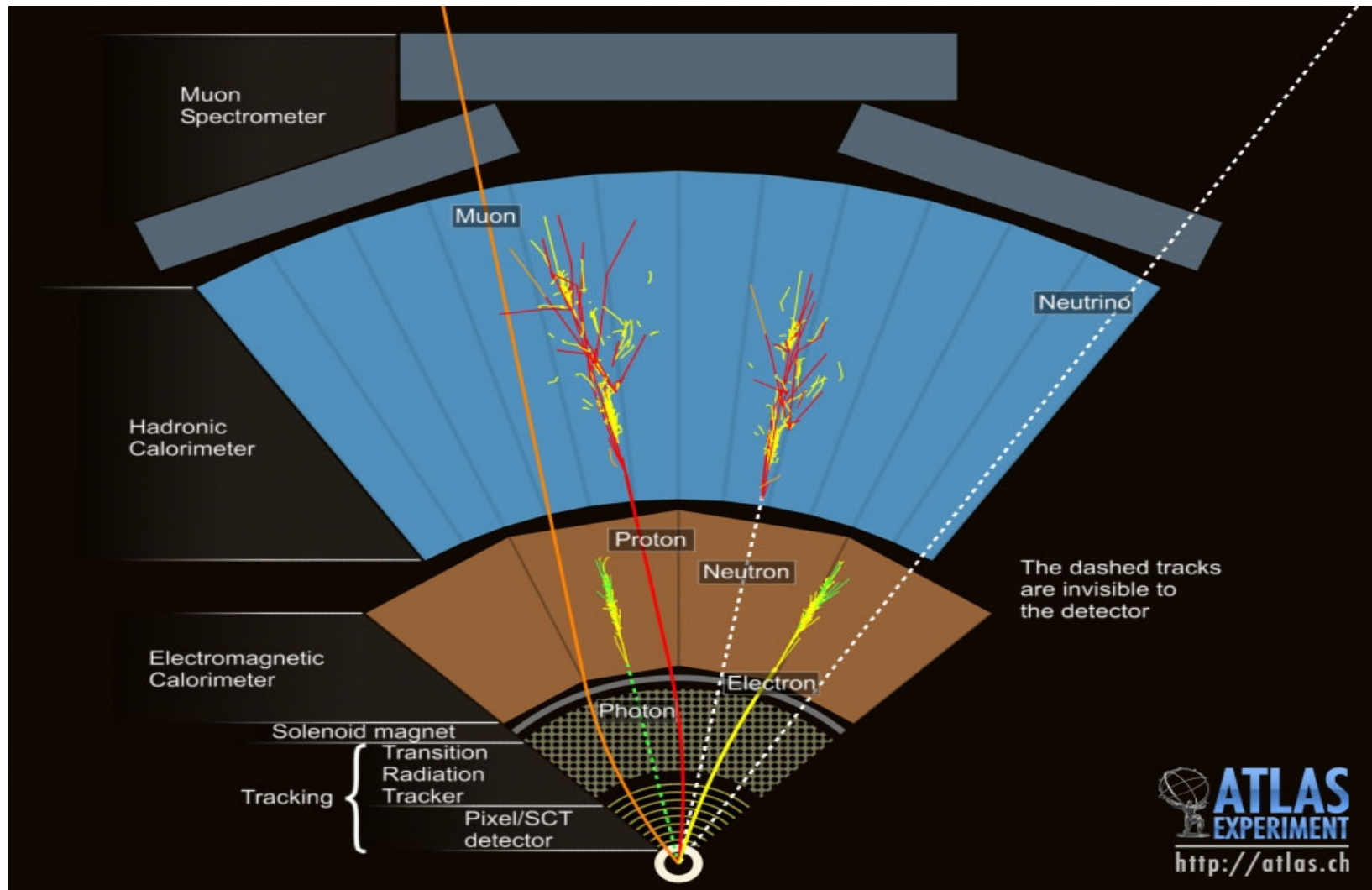
Overview

- Basic concepts of particle detection haven't changed in 50 years
- Major improvements in detector technology have played a critical role in field:
 - Size: Uncertainty principle tells us probing smaller structure requires higher energy
 - Speed: Search for rare processes requires high rate event collection
 - Complexity: Large number of channels (up to 10^8) and need to combine different detectors to measure all aspects of complex events

Classification of Particle Detectors: What Do We Measure?

- Charged Particles
 - Momentum: Determine trajectory in B field
 - Mass: More difficult; requires estimate of velocity
 - Energy: Deposited via EM interaction (ionization)
- Strongly Interacting Neutral Particles
 - Energy: Deposited via nuclear interaction
- Photons
 - Energy: Pair production followed by ionization
- Muons
 - No hadronic interactions and less brem than electrons
 - Can pass through lots of matter (energy loss by ionization loss)
- Neutrinos
 - Often observed by their absence: missing momentum
 - Weak interactions with nucleus (eg $\nu_{\mu} N \rightarrow \mu X$)

How It Works: An Example

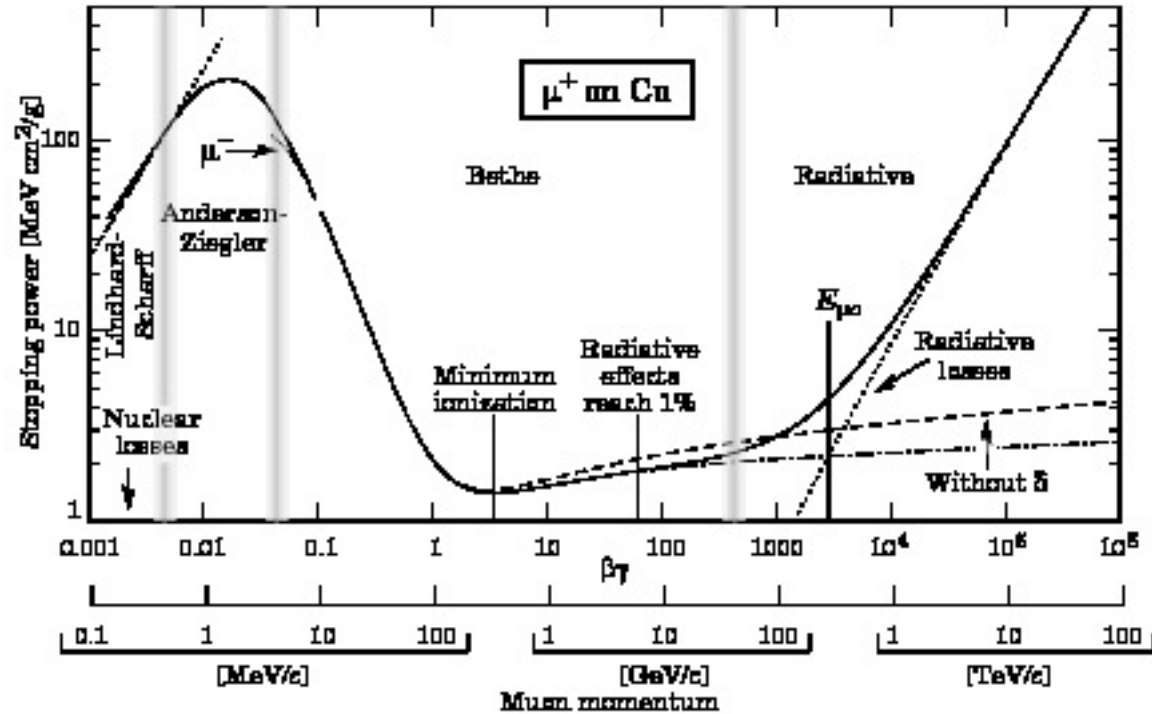


Interaction of Particles With Matter

- Except for hadron calorimeters (where nuclear interactions dominate are source of showers) and ν detectors, particle detection depends on EM interactions
 - Even for the exceptions: EM interactions dominate the detection of secondaries
 - Charged particles leave ionization trail
 - Detection of trail gives trajectory
 - Amount of ionization depends on momentum
 - Total energy deposited when particle stops measured by number of ionizing particles produced in shower
 - Statistical description of ionization energy loss
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Ionization Energy Loss: Bethe-Block Equation

- Particle with:
 - charge z
 - velocity $v/c=\beta$ and $\gamma=\sqrt{1/1-\beta^2}$
 - T_{\max} : maximum energy loss in a single collision
- traverses medium with:
 - Atomic mass and number A and Z
 - Density ρ
 - Ionization potential I
- $K/A = 0.307075 \text{ MeV/g}$ for $A=1 \text{ g/m}$

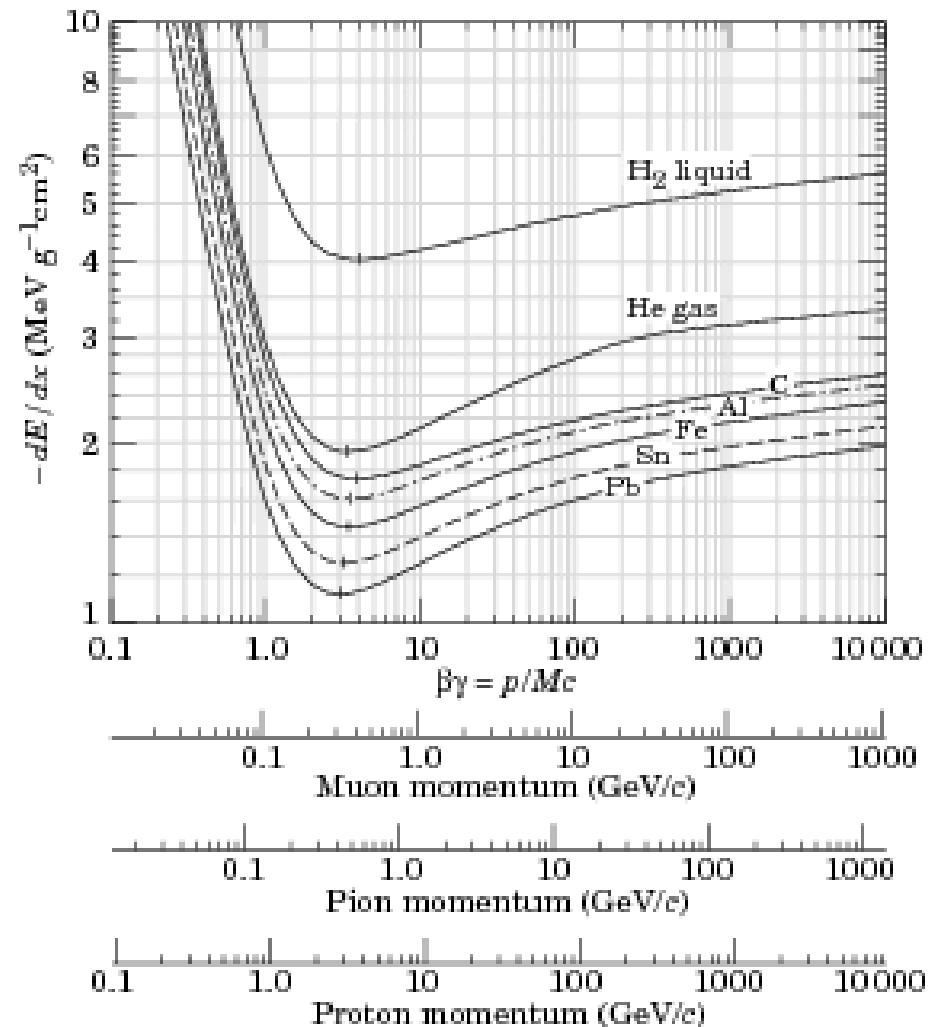


- Energy loss per unit length
- Quoted in $\text{MeV cm}^2/\text{g}$ where x is in μs , ρ =density x =distance

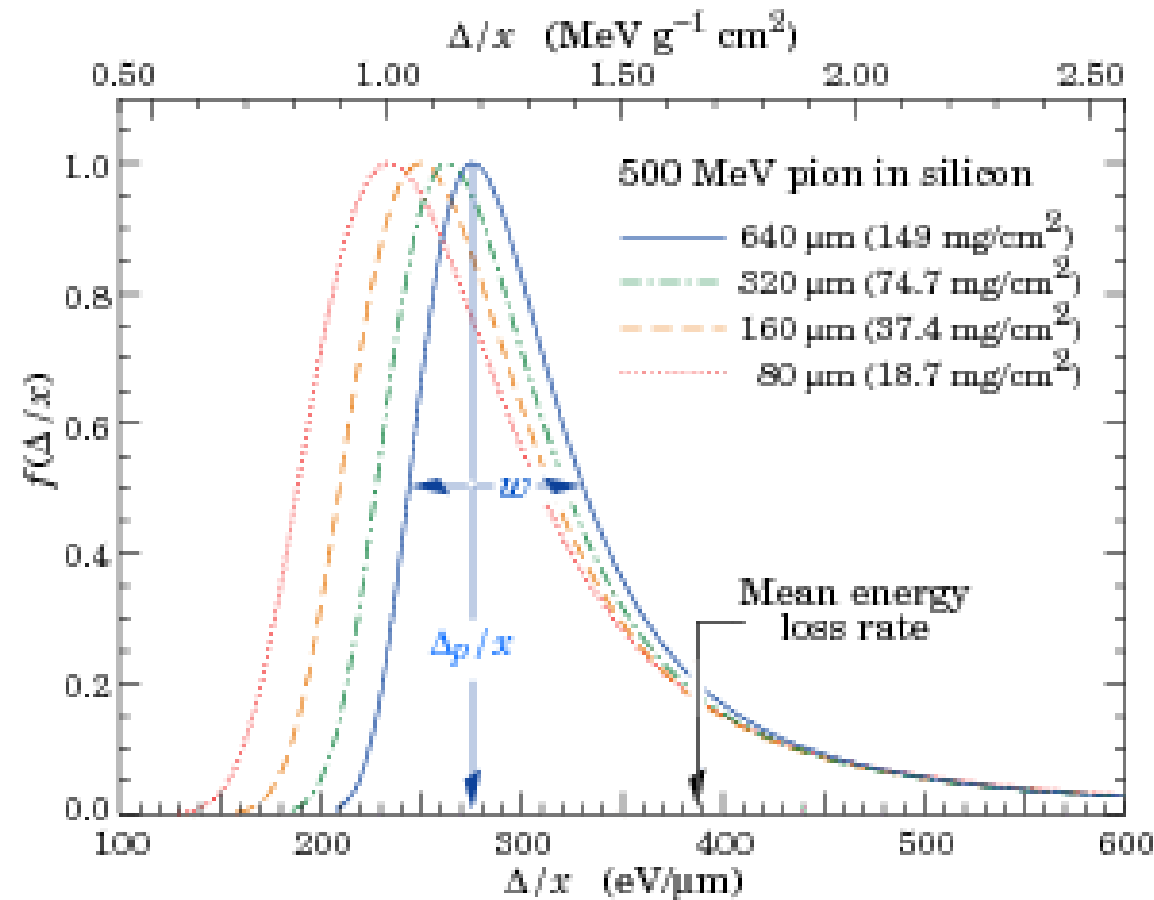
$$\frac{-dE}{dx} = K Z^2 \frac{Z}{2} \frac{1}{\beta^2} \left\{ \frac{1}{2} \ln \left(\frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right\}$$

More on Beta-Block

- Mean energy loss per cm:
 dE/dx depends on $\beta\gamma$
 - $(dE/dx)_{\min} \sim 1 \text{ to } 1.5 \text{ MeV cm}^2/\text{g}$
- Accurate to a few per-cent for $0.1 < \beta\gamma < 1000$
- Size of “relativistic rise” depends on density of medium
- Note: Beta-Block eq uses approx that incident particle heavy wrt mass of electron
 - Similar expressions for electrons

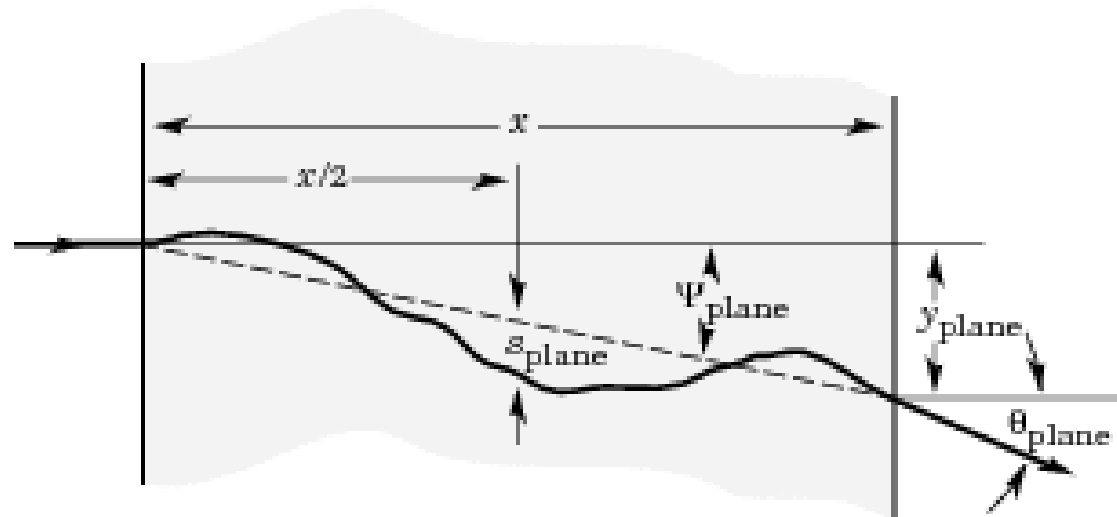


Large Statistical Fluctuations in Energy Deposition: Landau Distribution



- High energy tail: knock-on electrons (“delta-rays”)
- Best estimate of $\beta\gamma$: make multiple measurements and take truncated mean

Coulomb Scattering



- Change in momentum of particle dominantly caused by EM scattering with nuclei
- Scattering Cross Section: Rutherford Scattering

$$\theta_0 = \theta_{\text{plane}}^{\text{true}} = \frac{1}{\sqrt{2}} \theta_{\text{space}}^{\text{true}}$$

$$\theta_0 = \frac{13.6 \text{ MeV}}{\beta_{cp}} \approx \sqrt{x/X_0} \left[1 + 0.038 \ln(x/X_0) \right]$$

X_0 is called the
"radiation length:

$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A} \left\{ Z^2 [L_{\text{rad}} - f(Z)] + Z L'_{\text{rad}} \right\}$$

Tracking Detectors: Momentum Measurement (I)

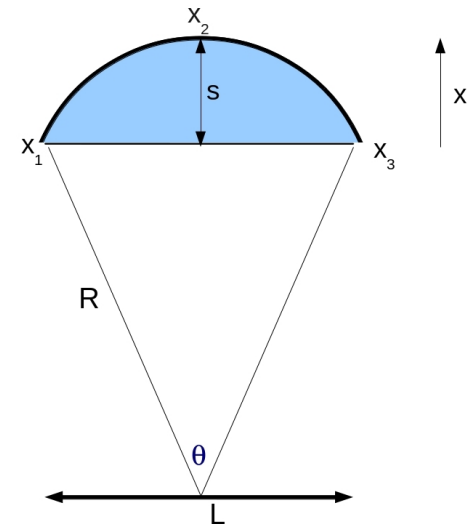
- Measure particle's trajectory and momentum
 - Can also measure ionization to identify species
- Trajectory determined from position of measurements
- Momentum determined from radius of curvature R when particle passes through magnetic B field
 - $P_T \text{ (GeV/c)} = 0.3 BR$
- R determined from measurement of sagitta s

$$\frac{L/2}{R} = \sin \frac{\theta}{2} \approx \theta$$
$$s = R \left(1 - \cos \frac{\theta}{2} \right) \approx R \left(1 - \left(1 - \frac{\theta^2}{8} \right) \right) \approx R \left(\frac{\theta^2}{8} \right) \approx \frac{0.3BL^2}{8 p_T}$$

$$s = x_2 - \frac{1}{2}(x_1 + x_3)$$

$$ds = dx_2 - dx_1/2 - dx_3/2$$

$$\sigma_x^2 = \sigma_x^2 + 2(\sigma_x^2/4) = 3/2 \sigma_x^2$$



(a la Mike Hildreth)

Tracking Detectors Momentum Measurement (II)

- For N=3 measurements, results on previous page give

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x}{s} \sqrt{3/2} = \frac{\sigma_x \cdot p_T}{0.3 BL^2} \sqrt{96}$$

- For N>10 measurements:

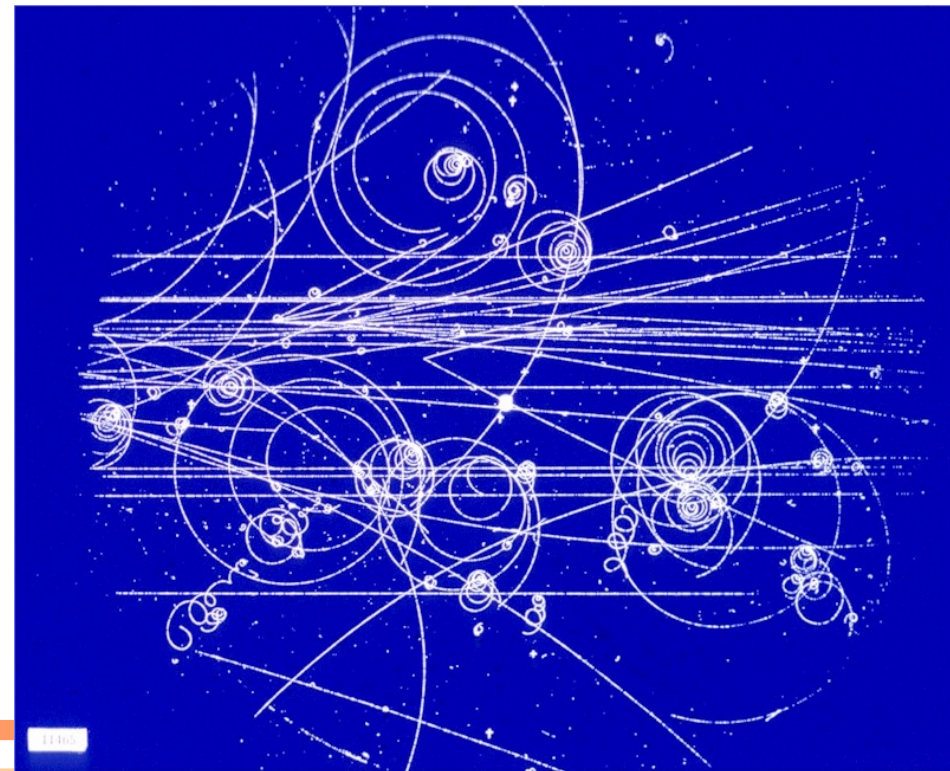
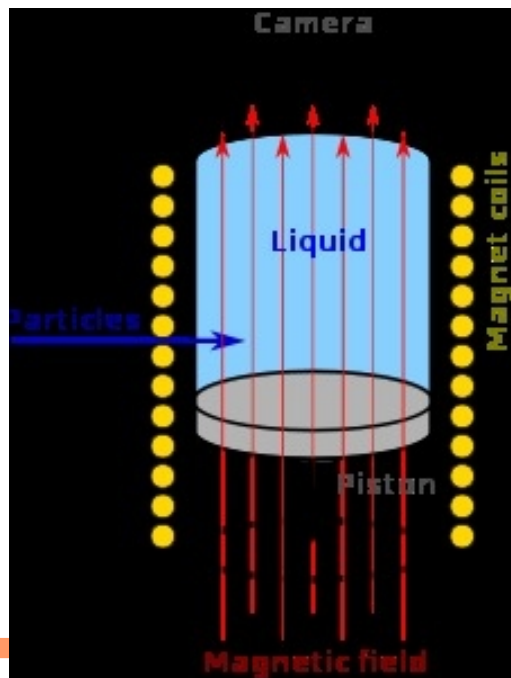
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_x \cdot p_T}{0.3 BL^2} \sqrt{720/(N+4)}$$

- Gluckstern, NIM 24 (1963) 381.

From Mike Hindreth

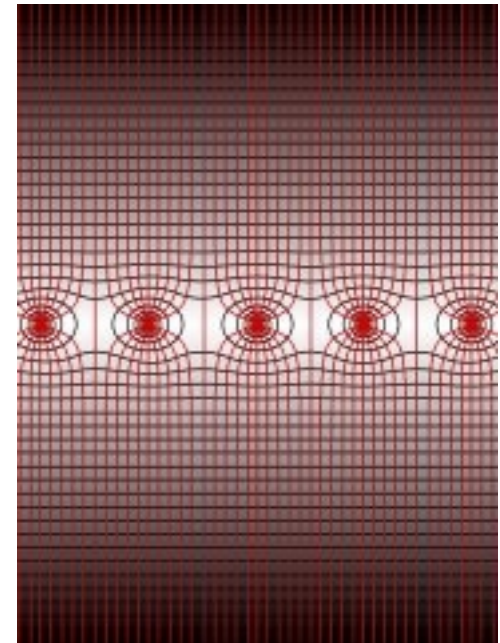
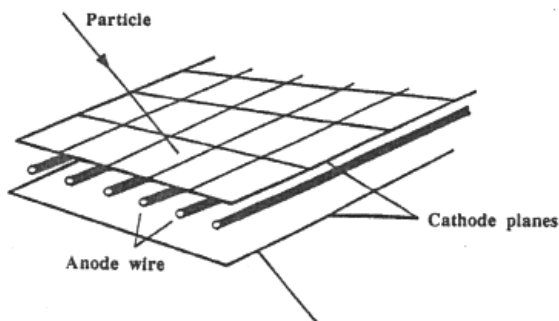
Charged Particle Detectors: Bubble Chamber

- Very important in early history of the field
- Charged particles leave tracks (bubbles in superheated liquid in metastable state)
- Not commonly used now
 - Slow
 - Requires scanning of pictures
 - But some specialized applications



Charged Particle Detectors: Proportional Counters

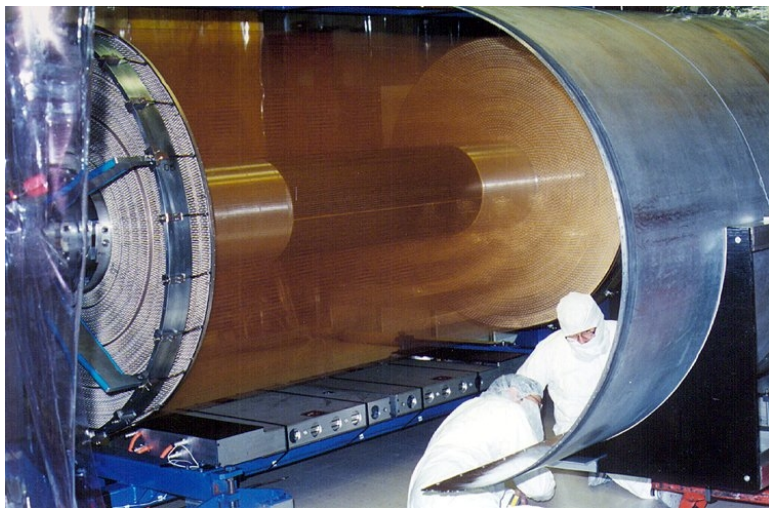
- Simplest Example: Single wire in a tube
 - Radial electric field $E(r) = E_0/r$
 - Thin wire means large field near wire
 - Ionization electrons drift towards wire and gain energy
 - These electrons ionize gas: avalanche process
 - At moderate voltage, collected charge proportional to initial ionization energy
 - At high voltage saturation: Geiger mode
- Instead of tube, can have multiple wire prop counter with wires or anode sheets to shape field



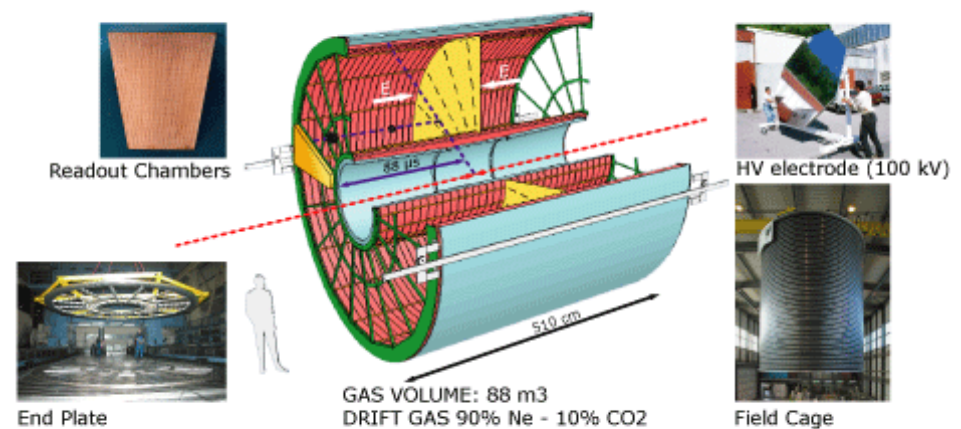
Charged Particle Detectors: Drift Chambers

- Position resolution of MPWC determined by wire spacing
- Can improve resolution by measuring drift time
 - Need fast start signal to start the clock
- Different geometries possible: flat chamber, cylindrical
 - Special case: Time Projection Chamber (TPC)

Babar Drift Chamber



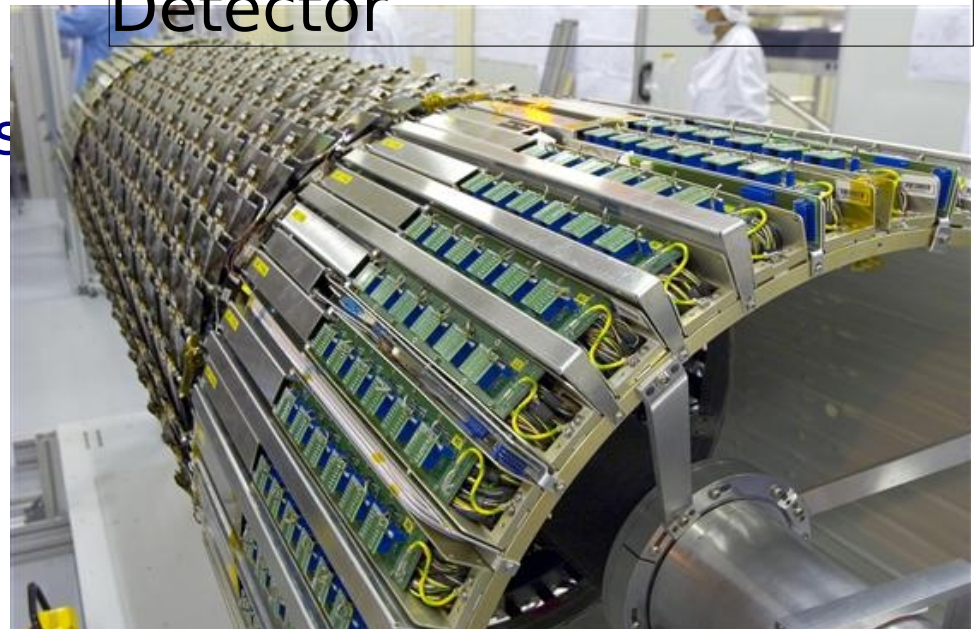
Star Time Projection Chamber 1



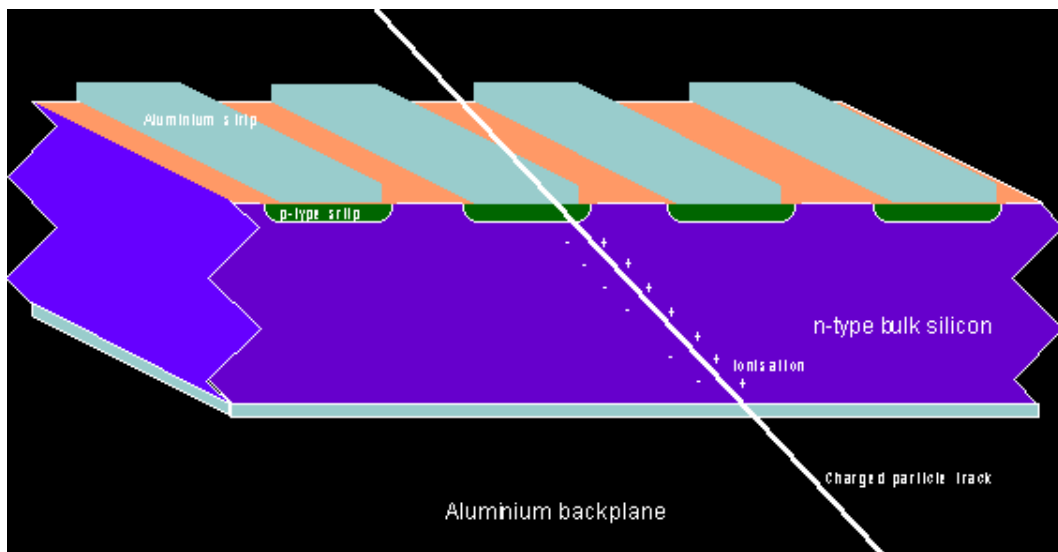
Charged Particle Detector: Silicon Detectors

- Silicon based detectors: natural outgrowth of semiconductor industry
 - Arrays of p-n junctions operated in reverse bias region
 - Depleted region with no mobile charge carriers and E field
 - Ionization moves in E field and is collected
- Very high granularity
 - Etching process to separate detector elements
 - Integrated front end electronics bonded to detectors
 - Two configurations: strips and pixels
- Good position resolution
- Radiation Hard

ATLAS Silicon Strip Detector



Particle Detection in Silicon



- Example: ATLAS SCT
 - Ionization in si leaves electrons and holes
 - Holes drift to to negatively charged p-type strips
 - Induce a charge in Al strips that are connected to readout electronics
 - Principle the same for pixels, but segmented in 2D

- Design issues:
 - Strips only give 2D information: Need stereo strips to infer z position
 - Silicon plus support structure and cooling mean lots of material: increases multiple scattering and conversions
 - Many electronic channels: 10^6 for strips, 10^8 for pixels
Can't read them all: zero suppression
 - Cost

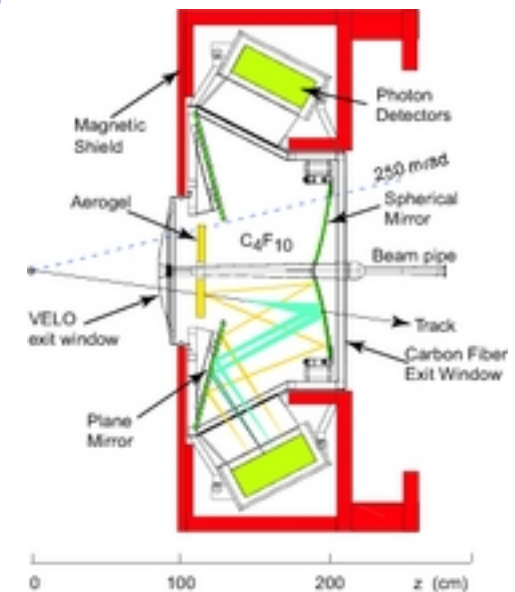
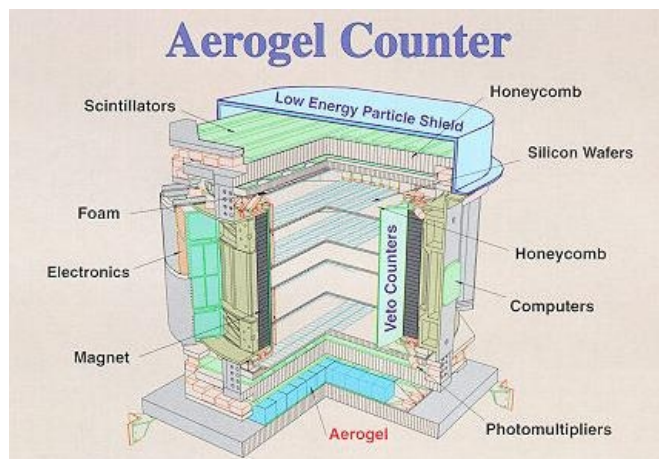
Charged Particle Detectors: Scintillation Counters

- In certain materials, ionizing particles excite atomic or molecular states that de-excite and give off light
- Photomultiplier tube used to read out signal
- Two kinds of scintillator:
 - **Organic:**
 - Molecular excitation emits light in UV
 - Converted to blue visible via fluorescence in wavelength shifter
 - Often used in “trigger” (fast response)
 - **Inorganic:**
 - Crystals (eg NaI)
 - High density: Particles stop
 - Main use is for calorimetry



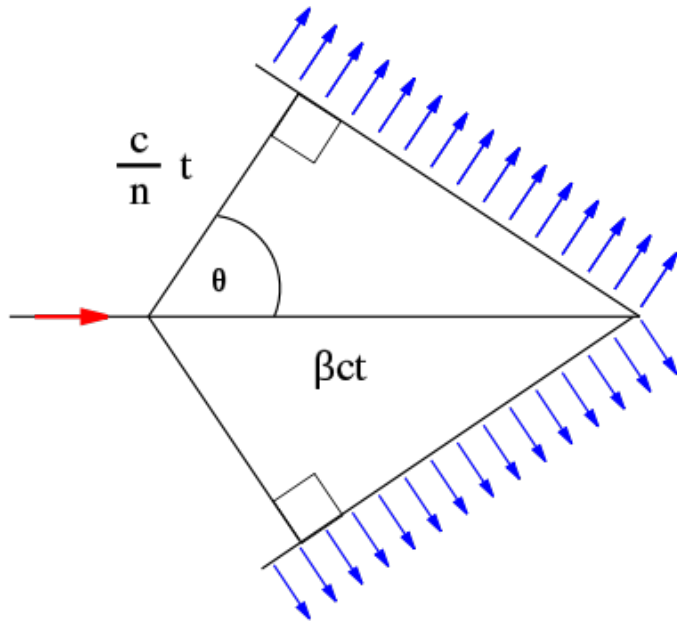
Charged Particle Detectors: Cherenkov Detectors

- Cherenkov light when particle's speed larger than speed of light in medium
- Light emitted in cone of fixed angle for given velocity
- Two types of detector:
 - Threshold: Separate particle species in given momentum range
 - Ring Imaging: Measure β from angle

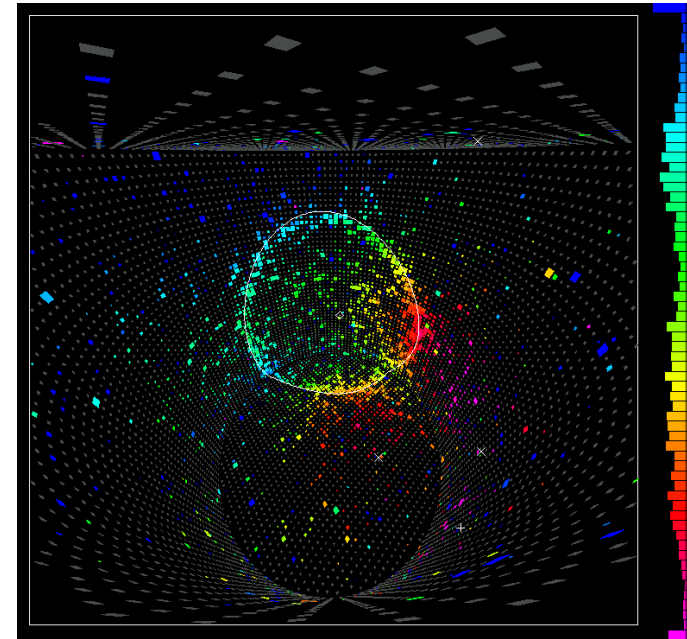


LHCb RICH Detector

More on Cherenkov Detectors



- Angle depends on medium and particle β
- Can distinguish species by measuring the angle (radius of cone where light detected)



- Example of an electron ring seen in super-K experiment
- Water cherenkov detector with photo-tubes on outside

Summary

- Charged particle detection relies on collecting ionization energy
- Trajectories measured from position of ionization
- Momentum measured from curvature in B field
- Amount of ionization sensitive to speed: together with momentum can deduce mass
- Wide variety of charged particle detectors exist
 - Cloud and bubble chambers
 - Wire chambers
 - Drift chambers
 - Silicon strip and pixel detectors
 - Scintillators
 - Cherenkov Detectors